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ROTARY ENGINE TECHNOLOGY

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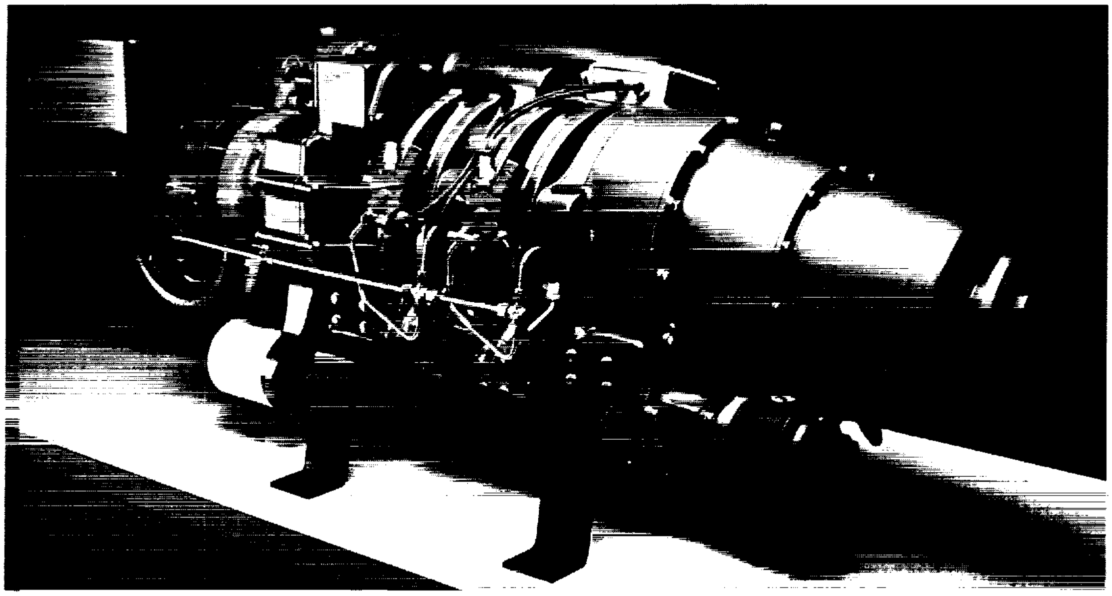
NASA's original goal in this program was to combine some of the better features of reciprocating and gas-turbine engines, thus obtaining a superior powerplant for light aircraft and a host of related uses. Based on a series of engine and aircraft/mission studies conducted in the early 1980's, the rotary (Wankel) engine was perceived to have many of the desired features and was judged to be capable of considerable further development. At the time, existing automotive rotary engines had demonstratably high power outputs in a compact, smooth-running, and reliable package, but were less fuel efficient than comparable reciprocating engines. Accordingly, the basic thrust of the NASA Rotary Engine Technology Enablement Program was (and is) to bring the rotary's efficiency up to the level of a comparably sized diesel, without sacrificing its other desirable features.

Overview of NASA Objectives



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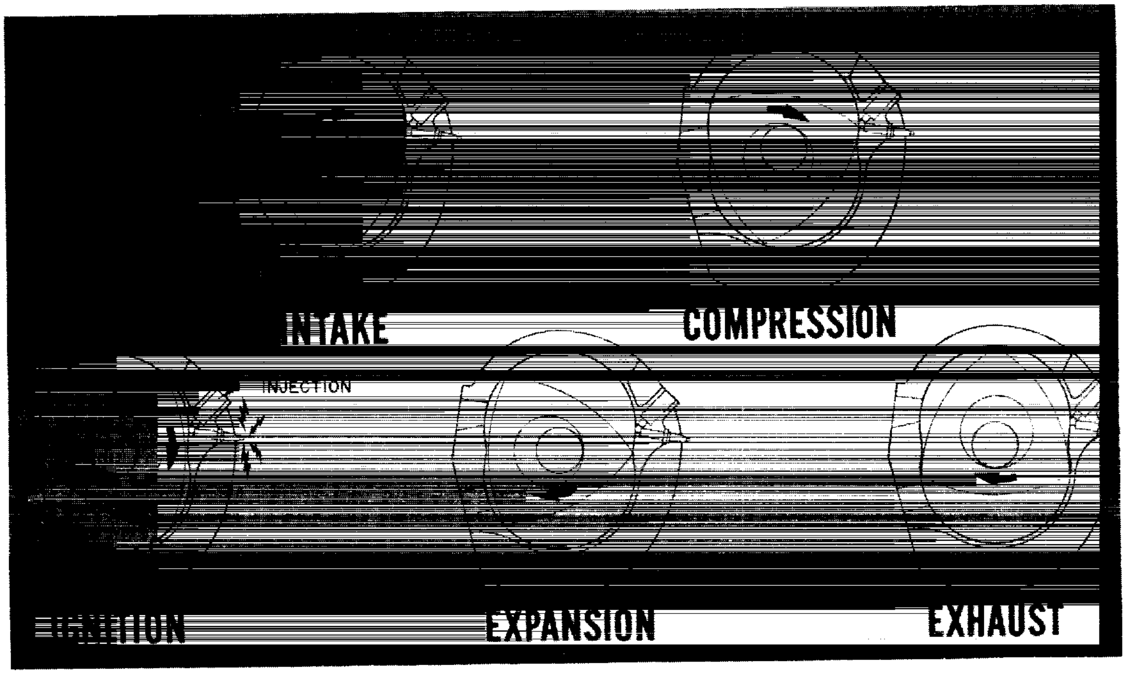
- **Multifuel capability (gasoline, jet, diesel, and alcohol fuels).**
- **Cruise BSFC: 0.36 lb/hp-hr, or better.**
- **Power density (maximum): 5 hp/in.^{3}, or better.**
- **2000-hr durability (TBO).**
- **Altitude capability: 28 000 ft or more (depends on application).**
- **Modular design (family-of-engines concept).**
- **Manufacturing cost competitive with comparable reciprocating engines.**

Specific objectives of the program, believed to be accomplishable by the end of 1991, are shown in the figure above.

Stratified-Charge Rotary Engine Concept



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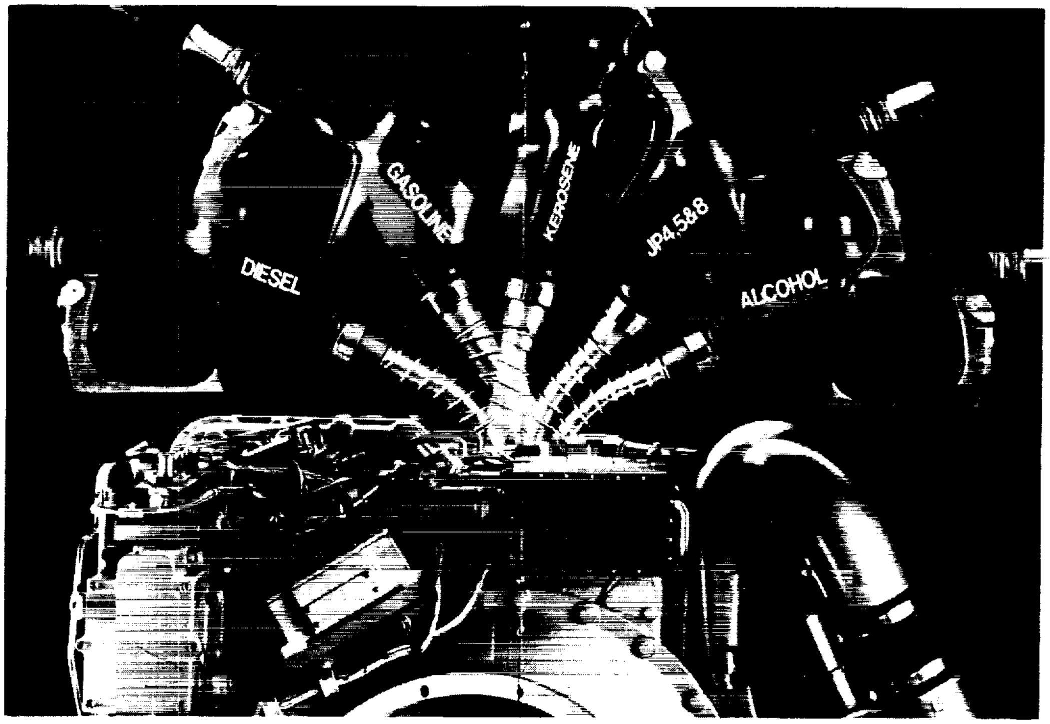
A particular form of the rotary engine, the so-called stratified-charge rotary engine (SCRE) was considered to have the best chance of meeting the objectives. In this embodiment (see chart), the primary structure consists of a triangular rotor which is given a hula-hoop type motion within a trochoidal housing. The rotor's motion, guided by an eccentric crank and timing gears, is such that the rotor makes one complete revolution for three revolutions of the crank, while its sealed tips maintain contact with the trochoid walls. Thus, each of the rotor flanks defines a sealed working space in which the familiar strokes of intake, compression, combustion/expansion, and exhaust are accomplished. One complete four-stroke cycle is accomplished per revolution of the crankshaft.

In common with other versions of the Wankel engine, the SCRE has clear virtues of compactness, low weight and vibration, high power and simplicity. The stratified-charge version, however, employs diesel-type, timed, high-pressure fuel injection, *across an ignitition source*, to maintain positive control of the combustion event. By appropriate control of the fuel injection and ignition timings, the combustion can be controlled to a point where cetane and octane requirements on the fuel are irrelevant. This immediately leads to multifuel capability. Clearly, it also leads to major challenges and opportunities in understanding and optimizing this form of combustion.

Prior Accomplishments (FY '89 and earlier)
Any fuel, anytime, in any combination



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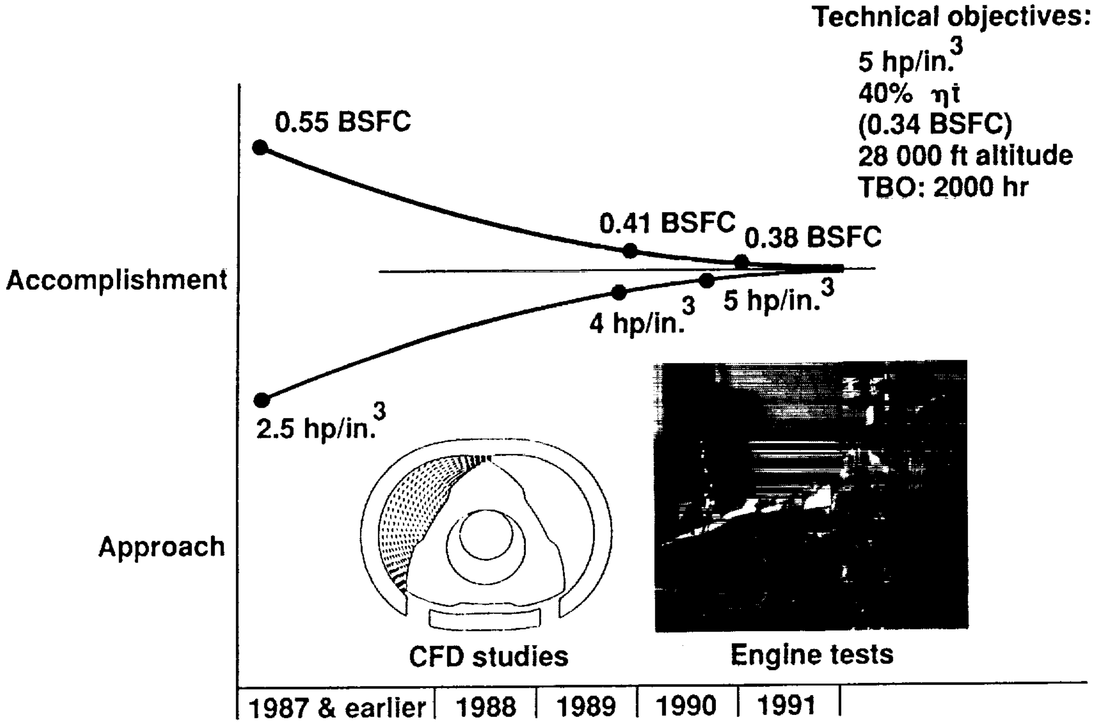
A program addressing the previously stated objectives for the SCRE has been underway since the mid-1980's and is now entering its final phase. The effort has been structured to consist of major R&D contracts with Curtiss-Wright and Deere, supported by smaller NASA in-house efforts and grants with several Universities.

One of the major objectives, multifuel capability, has been demonstrated. Engine tests with automotive and aviation gasoline (avgas), diesel fuels, kerosene/Jet-A, JP4, 5, and 8, and alcohol fuels have shown virtually identical thermal efficiencies and no octane/cetane dependence. This is inherent in the stratified-charge combustion concept which is particularly well suited to the rotary engine. This alone makes it usable and thus, saleable, in parts of the world where specific fuels, e.g., avgas, may be unavailable or prohibitively expensive.

Major progress against other objectives was recorded as well. Specific power was nearly doubled, to above 4 hp/in.^{3} by the end of FY '89. At the same time, cruise BSFC was improved about 20 percent from its original baseline and had reached 0.42 lb/hp-hr by late 1989. These gains also demonstrated the power of CFD methods for improving combustion in the rotary engine and the ability of turbocharging to improve BSFC as well as power. One CFD-driven improvement, the so-called non-shadowing or fan type main fuel injector spray pattern, alone accounted for 14 percent out of the 20 percent BSFC improvement. The other 6 percent was due to turbo optimization.

Recent Accomplishments (Early '91)

Rotary Engine Performance Improvement



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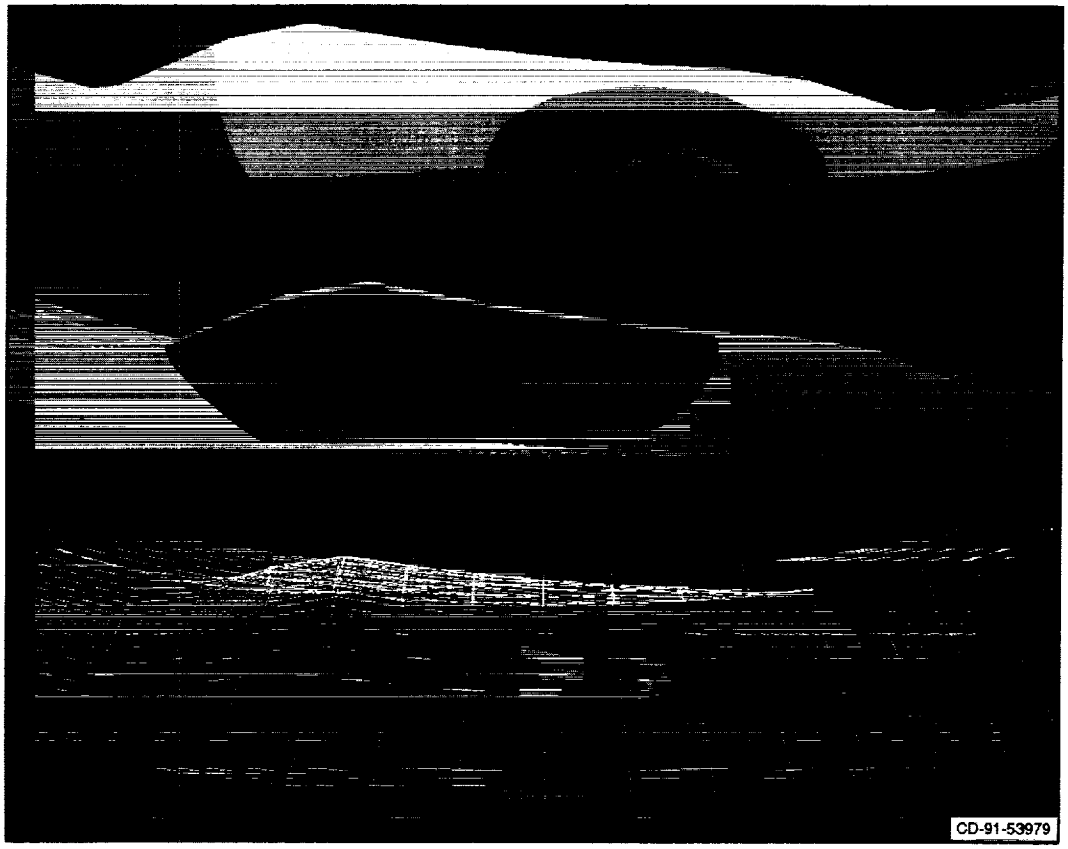
Following the precedent described above, the recent efforts have continued to rely heavily on further CFD-derived combustion system modifications and continued turbocharger matching and optimization. The so-called non-shadowing spray was further improved to achieve 0.41 BSFC by early 1990. A second CFD-related modification, the dual-spray pilot injector, experimentally yielded a 0.39 BSFC by January 1991. Most recently, the dual ignition housing design, which also derives from CFD studies, is currently under test and yielding BSFCs of around 0.38.

In addition, tests with higher levels of turbocharging yielded a maximum specific power output of 5.0 hp/in.^{3}, thus satisfying another of the original objectives. In the process, it was observed that the test engine was running richer than would be desired for good fuel economy. This indicates a need for more air throughput, which could be obtained either by increasing the exhaust port area or by further raising the turbocharger discharge pressure and flow. The former approach was selected since the tests also showed a marginal peak pressure condition at high powers.

Additional tests involved a ceramic-coated rotor developed in a companion SBIR effort. Short-term durability was demonstrated in 100 hr of running, and the heat transfer results appeared to be consistent with computer code predictions.

Other accomplishments include two new CFD codes and a new cycle/system simulation code now operational and in the validation process. Fuel spray and airflow visualizations are being conducted to obtain validation data. Two new apex seal material candidates (Si_3N_4 and a Deere proprietary sintered metallic) have demonstrated 6000-hr TBO potential.

Rotary Engine CFD Code Development and Applications

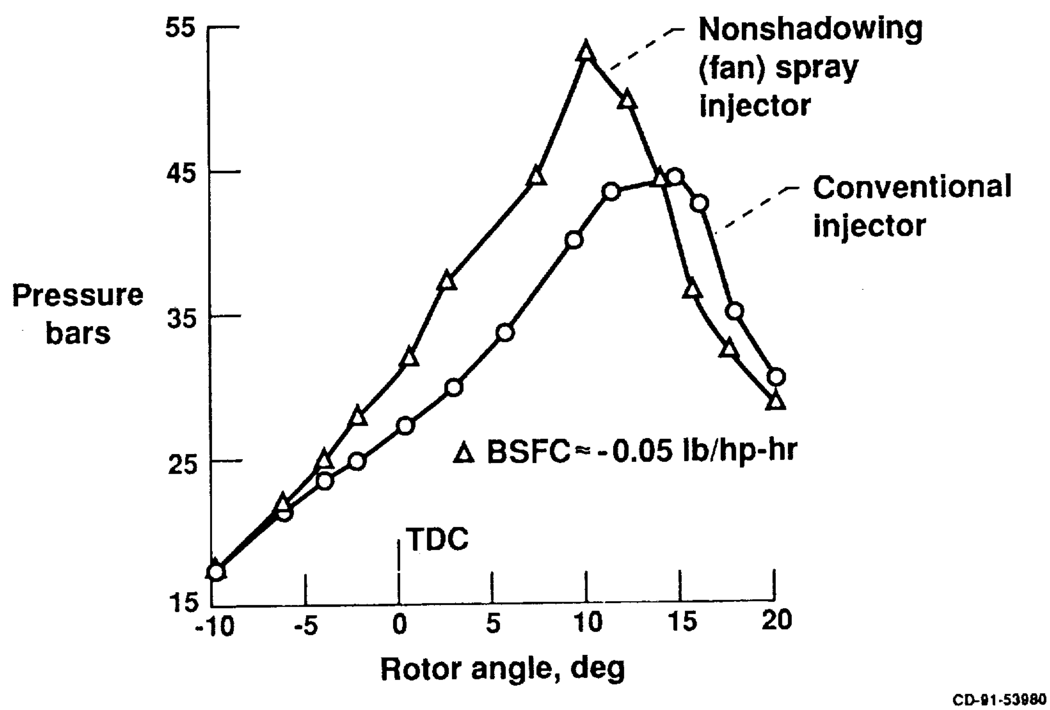


As previously noted, three-dimensional, turbulent, Navier-Stokes computer codes to simulate the airflow inside of a rotary engine have been under development for several years. These include appropriate submodels for fuel spray phenomena and combustion. Historically, the earliest and most extensively applied code is that developed at Princeton University and improved and extensively used at Deere. A comparable code, offering potential advantages in CPU speed, sensitivity, and user-convenience features, has been developed at Lewis by a NASA-Sverdrup team. This code has recently become operational and is now beginning the assessment/validation process.

The availability of such codes now allows analytical studies to be made, in as much depth and detail as desired, of the airflow, fuel spray, evaporation, mixing, and combustion processes in the rotary engine. The accompanying chart illustrates typical gridwork, fuel droplet trajectories, temperature profiles, and fuel concentration near top-dead-center at a moderate speed/load condition.

Early studies consistently showed evidence of slow and nonuniform fuel-air mixing in the pocket region. The shadowing effect of one fuel jet directly upstream of another was one of the primary contributors to this problem. The solution - which seems almost obvious in retrospect - was to arrange the fuel sprays into a two-dimensional, fan-shaped pattern, rather than the diesel type conical spray that was used previously. In this arrangement (previously referred to as the non-shadowing spray), no fuel jet is the wake of an upstream one, and all receive the full momentum flux of the local airflow field.

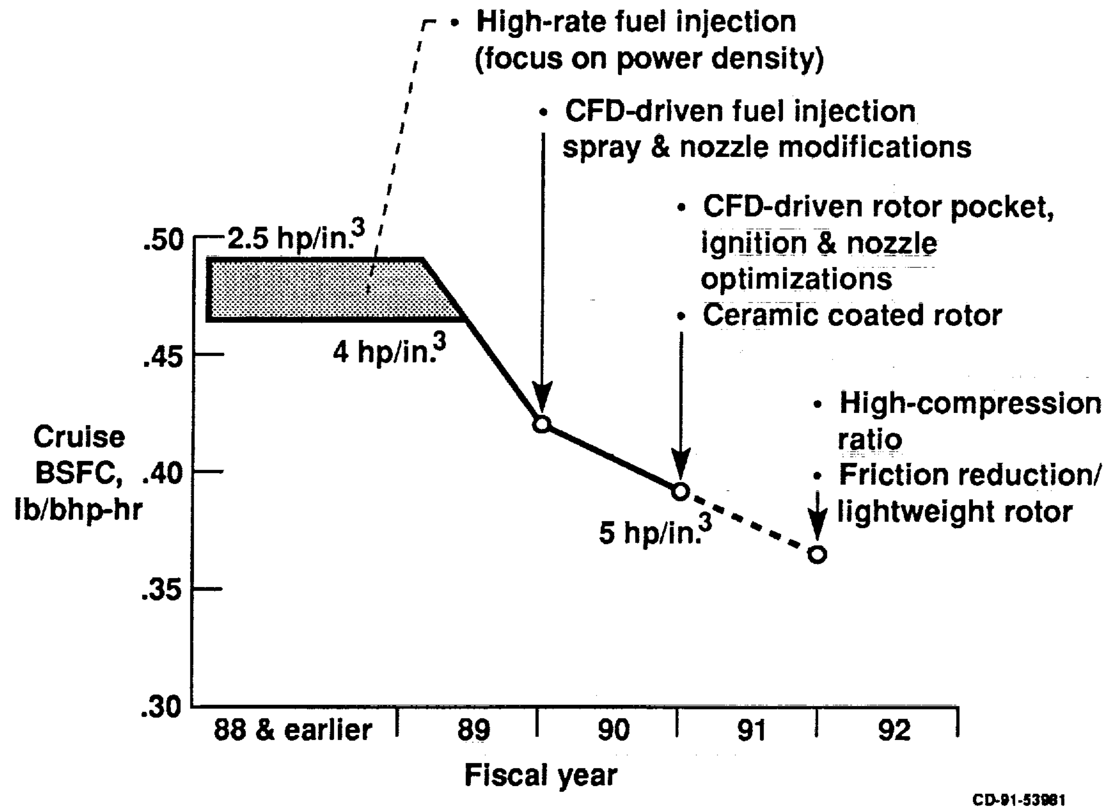
Rotary Combustion Improvements Resulting From CFD Work



The advent of believable CFD methods has had a revolutionary impact on rotary engine combustion since about 1988. The difference - from the viewpoint of the rotary engine research teams - has been as if we were given a powerful searchlight instead of a single candle with which to explore a very large cave. The flow and combustion phenomena within the stratified-charge rotary are so unlike their diesel or turbine counterparts that prior experience with other heat engines provided no useful guidance whatsoever in the combustion area. On the contrary, the initial choice of a conventional, diesel type conical spray pattern for the main fuel injector proved to be exactly opposite to what the rotary engine really needs.

As previously mentioned, numerous improvements to the rotary combustion system have now been identified by the CFD studies. The first of these, the so-called non-shadowing, or fan spray, pattern for the main fuel injector nozzle, alone resulted in an *immediate* improvement of about 10 percent in cruise BSFC when tested in the engine rig. As illustrated in the accompanying chart, the fan spray resulted in faster fuel-air mixing and, in turn, a faster rate of pressure rise in the combustion chamber, a higher peak pressure, and a closer approach to the ideal Otto cycle. In the first experiments with this innovation the rig engine improved from a BSFC of 0.48 to 0.43 at cruise conditions within a few weeks. This is believed to be *the first time in history that a CFD-derived modification has led to an actual improvement in a real engine.*

Rotary Combustion Improvements (cont.)

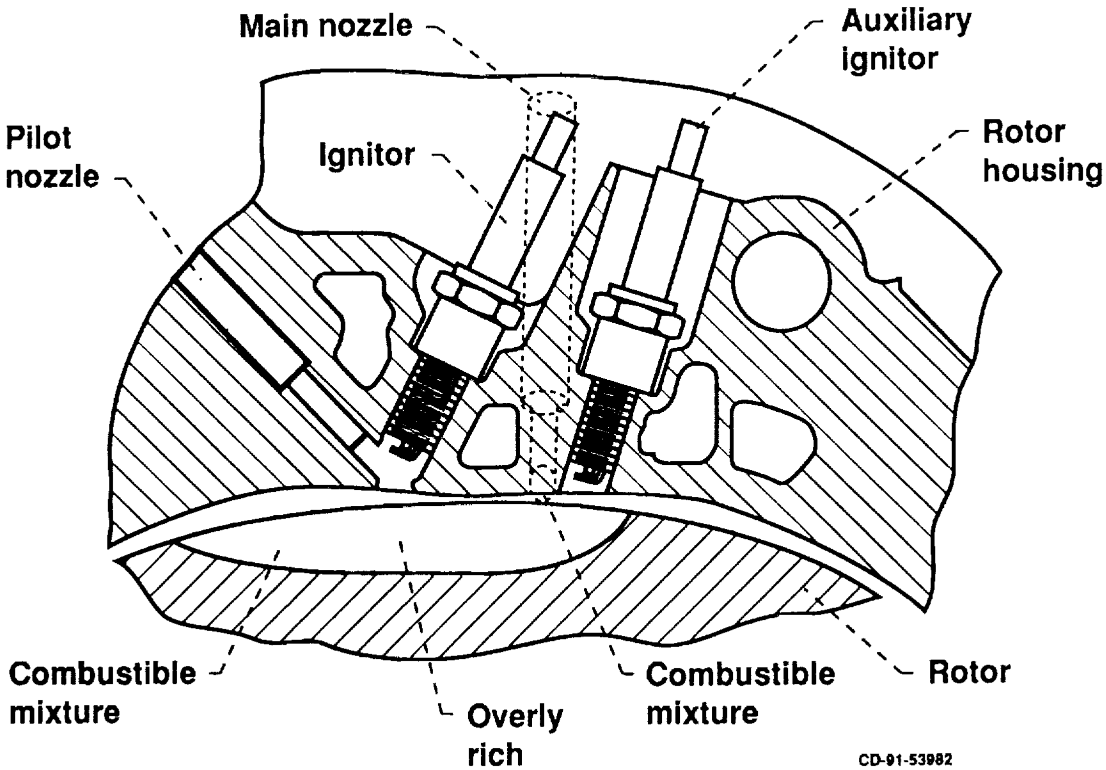


The chart summarizes the past and expected BSFC improvements. Following the major accomplishment described on the preceding page, the BSFC of the fan spray engine configuration was further improved to about 0.41 during 1990. This entailed experimental optimization of the engine/turbocharger match and injector details such as hole size, number, fan angle, and fuel pressure.

Additional tests during 1990 addressed the issue of maximum power density. The objective level of 5 hp/in.^{3} was achieved, albeit with some difficulty. This is a factor-of-two improvement over the original baseline and over contemporary automotive rotaries. During these tests, it was noted that the engine was unable to pass enough airflow to maintain near-optimum mixture ratios at high speeds and loads. A new housing with an enlarged and variable exhaust port area was designed to handle the increased airflow without higher boost pressures.

Other CFD-related improvements include the dual spray pilot injector, which demonstrated 0.39 BSFC in January 1991; the dual igniter housing, which is currently running at about 0.38 BSFC; the variable exhaust port housing, which should improve efficiency at the higher power levels; and two modified-pocket rotors (compact pocket and dual pockets), one or both of which should achieve the predicted 0.36 BSFC level. Finally, the time-honored thermodynamic expedient of increasing the compression ratio above its present, conservative value of 8.4:1 may well result in a cruise BSFC below 0.36.

Benefit of Dual Spark Ignition



The dual-spark igniter concept, illustrated schematically in the accompanying chart and currently under test at Deere, is one of the several improvements that have resulted from the CFD analyses. As the illustration suggests, the additional spark plug provides for immediate ignition of a secondary region of combustible mixture. Otherwise, flame propagation is retarded by an intervening layer of overly rich fuel-air mixture. This results in a faster pressure rise, higher peak pressure, and improved thermal efficiency, exactly as was previously shown for the fan spray injector. Currently, a BSFC of about 0.38 lb/hp-hr is being shown. Moreover, the benefit from this concept is over and above the benefits due to the fan injector and dual-spray pilot, although individual benefits are not expected to add together linearly (since they are collectively subject to an upper limit set by basic thermodynamics).

Perhaps the most promising of the planned modifications are those involving changes to the rotor's combustion pocket-size, shape, location, or any combination thereof. These were deferred until late in the program in order to develop confidence in the CFD results. New rotor castings are relatively expensive in small lots and involve substantial lead times. Nevertheless, it is expected that at least two new pocket configurations will be tested during FY '91 and will result in meeting the present cruise BSFC objective.

Issues and Problems

- **Deere & Co. plans to divest itself of the rotary engine division by November 1991.**
- **NASA response: Develop plans & contract modification to complete the Deere contract by November 1991.**

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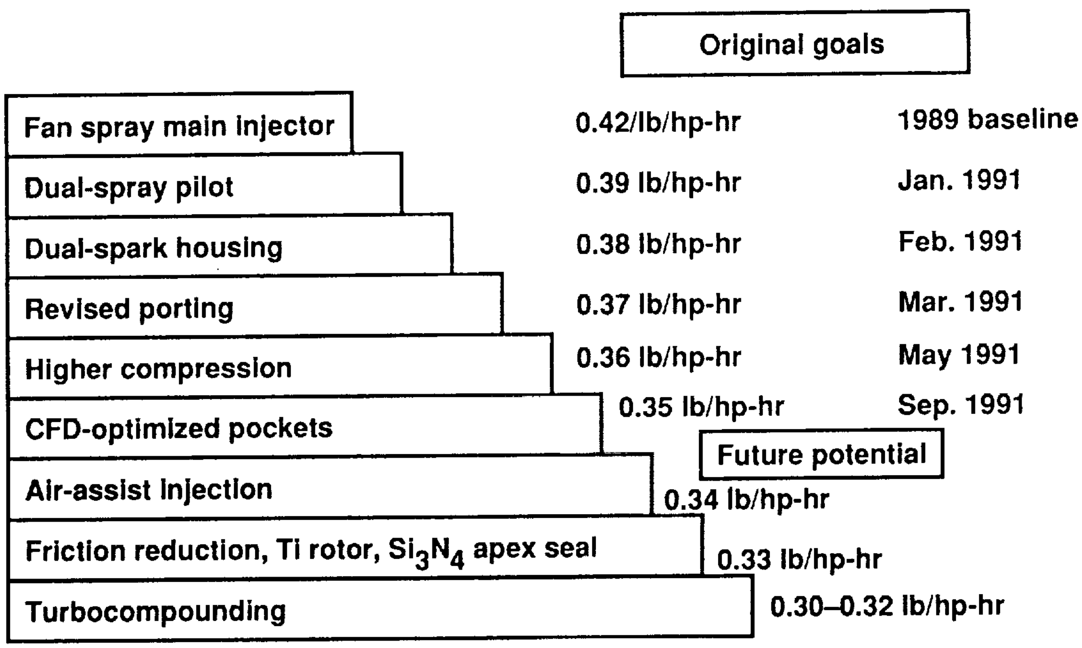
In September 1990, Deere and Company announced plans to divest itself by November 1, 1991, of its Rotary Engine Division (REDIV) in New Jersey, where the majority of the NASA rotary technology enablement program is being carried out. This announcement was accompanied by a substantial reduction in force and cessation of all company-sponsored efforts at the REDIV facility. Continuing efforts will address the completion of the NASA and other major contracts "to the customer's satisfaction."

This posed difficulties for NASA since the original program was planned and scheduled for completion at the end of FY '92. The unexpected acceleration of the program affects several Universities and small companies as well as Deere and NASA. NASA has responded by developing plans to complete a worthwhile subset of the original plans by November 1991. Nevertheless, an acceleration of one full year out of two years remaining cannot be accommodated without something being lost. The major loss as now perceived is that maximum power and best BSFC will not be obtainable in a single build of the test rig. At the end, there will be no engine which is capable of 5 $hp/in.^3$ *and* a 0.35 to 0.36 cruise BSFC. A final step, which may well require a structural redesign for higher peak pressures, will still be needed. Also needed are tests of further known improvements, such as ceramic applications and turbocompounding, which could not be fitted into the compressed schedule.

Currently, the search for a successor is underway in earnest. Although the present authors are not privy to this process, we can certainly say that much will depend on the identity, objectives, and capabilities of the successor(s). At this writing we cannot predict whether the complete engine will ever be built, or by whom, or whether the additional known improvements will ever be tested.

Summary

BSFC Improvement steps - accomplished or planned



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Despite the issues just cited, it is clear that major and perhaps revolutionary progress has been accomplished in the NASA Rotary Engine program over the past few years. This includes multifuel capability, 5 hp/in.^{3}, a cruise BSFC rapidly approaching this year's goal of 0.35 to 0.36 lb/hp-hr and highly encouraging wear-rate indications for ceramic apex seals. Highly sophisticated new computer codes have been developed and applied to generate many of the specific improvements enumerated in the chart above.

Because of the limited time, unfortunately, it now appears that the maximum-power and best-BSFC objectives will not be demonstrable in the same engine and that several known improvements cannot be exploited. Depending on who becomes the successor to Deere and on resources yet to be identified, the potential nevertheless exists to achieve a cruise BSFC as low as 0.30 lb in a compact, lightweight, multifuel rotary engine.